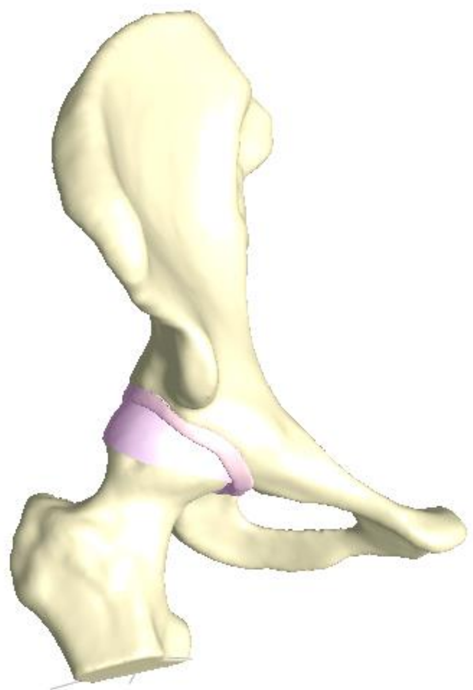
Introduction to Finite Element Modeling for Biomechanics

ME603, UW-Madison

Spring 2019

Corinne R. Henak

Welcome to Spring 2019!
Please complete quiz 1



Outline for today

- Course objectives, overview and resources
- What is biomechanics?
- Introduce computational and finite element modeling
- Rationale for FEM in biomechanics
- FEM workflow
  - FE solvers
- Designing studies
- V&V intro (methods to establish confidence)
- User responsibilities
- Course project
  - Project proposal due next week

Course Objectives

By the end of the semester, students will be able to:

- Define the FEM, explain its mathematical basis, and articulate alternatives.
- Justify the selection of a constitutive model for a particular modeling application.
- Complete verification analyses.
- Design and complete validation analyses.
- Describe the user's responsibilities in FEA.
- State benefits and limitations of FEA for biomedical applications.
- Build and analyze a finite element model, and present relevant results.
- Generate research questions that can be appropriately addressed using FE models, and design modeling protocols to address those questions.
- Critically review publications reporting FE analyses.

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Course Overview

- Theory
  - Continuum mechanics
  - Constitutive modeling
  - Finite element modeling
- Guidelines for responsible use of FEA
  - V&V, sensitivity studies
- Hands-on practice with FE models
  - Labs (will require out-of-class time)
  - Semester project

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Course Overview (2)

- Course documents will be posted on Canvas
  - Many assignments with be submitted on Canvas
- The syllabus will change over the semester
- How to reach me:
  - Office: ME3031 (hours M 8-9 am

    or by email appointment)
  - Online: Canvas chat (W 8-9 pm)
  - Email: chenak@wisc.edu

Really.
Email me!
Early in the semester, especially if you have a standing conflict with the scheduled time.

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Course Resources: Page 1

- There is no textbook for this course.
- There is a lot of material available to you for free:
  - FEBio Manuals. Available online: www.febio.org.
  - Nonlinear Finite Elements for Continua and Structures, 2nd Ed, Belytschko, Liu, Moran, Elkhodary. ISBN: 978-0-470-01832-3. Available online (UW library).
  - The Finite Element Method: Its Basis and Fundamentals, 6th Ed, Zienkiewicz, Taylor, Zhu. ISBN: 0-7506-6320-0. Available online (UW library).
  - The Elements of Continuum Biomechanics, Marcelo Epstein, Print ISBN: 9781119999232, DOI: 10.1002/9781118361016. Available online (UW library).
- There are some textbooks that are not freely available, but are worth considering if you want to pursue this topic further:
  - Nonlinear Solid Mechanics, Gerhard A. Holzapfel.
  - Nonlinear Continuum Mechanics for Finite Element Analysis, Javier Bonet and Richard D. Wood.

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Course Resources: Page 2

Publications that may be useful throughout the semester. ASME V&V Guide Overview

- Burkhart et al., *J Biomech*, 2013 (V&V, bone mechanics focus)
- Henninger et al., *Proc I Mech E Part H*, 2010 (V&V, sensitivity studies)
- Anderson et al., *Comp Method Biomech Biomed Engg*, 2007 (V&V, sensitivity studies)
- Viceconti et al., *Clin Biomech*, 2005 (guide for publishing/reviewing FEA manuscripts for Clinical Biomechanics – short but useful)
- Henak et al., *J Biomech Eng*, 2013 (patient-specific computational mechanics review)
- Viceconti et al., *J Biomech*, 2015 (perspective on *in silico* medicine)
- Erdemir et al., *J Biomech*, 2012 (reporting guidelines, a very detailed checklist, includes some multiscale considerations)
- Wilson et al., *Med Eng Phys*, 2005 (role of models, cartilage-centric)
- Laz and Browne, *Proc I Mech E Part H*, 2010 (probabilistic methods, beyond what was covered in lecture)
- Ateshian et al., *J Biomech*, 2015 (contact mechanics review)
- Search on PubMed or Google Scholar for more.

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What is biomechanics?

"Biomechanics is mechanics applied to biology."[1]

- Other definitions include:
  - "Biomechanics is the study of how physical forces interact with living systems."[2]
  - "In short, biomechanical engineering is the combined use of mechanical engineering principals and biological knowledge to better understand how these areas intersect and how they can be used together to potentially improve peoples' quality of life."[3]
- Mechanics are important in diseases (across length scales). Fundamentally, we study biomechanics because "Biology can no more be understood without biomechanics than an airplane can without aerodynamics."[1]
- In this course, we will focus on biomechanics in the solids/poroelastic materials realm. Fluid mechanics will not be covered.

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[1]Fung, Mechanical Properties of Living Tissues, 1993. [2]Ethier and Simmons, Introductory Biomechanics, 2007. [3]Stanford Biomechanics Program http://me.stanford.edu/groups/bme/faq.html.

What are computational models?[1]

- Numerical methods approximately solve problems without analytical solutions
- Types of numerical methods
  - Finite element (uses weak form of governing differential equations)
  - Finite difference (replaces differential equations with difference equations)
- In the case of solid mechanics FE, the equations are:
  - Equilibrium or motion equations
  - Constitutive equations
  - Compatibility conditions (BCs/LCs)

[1]Moaveni, Finite Element Anaysis: Theory and Application with ANSYS, 2008.

Role of Computational Models in Biomechanics

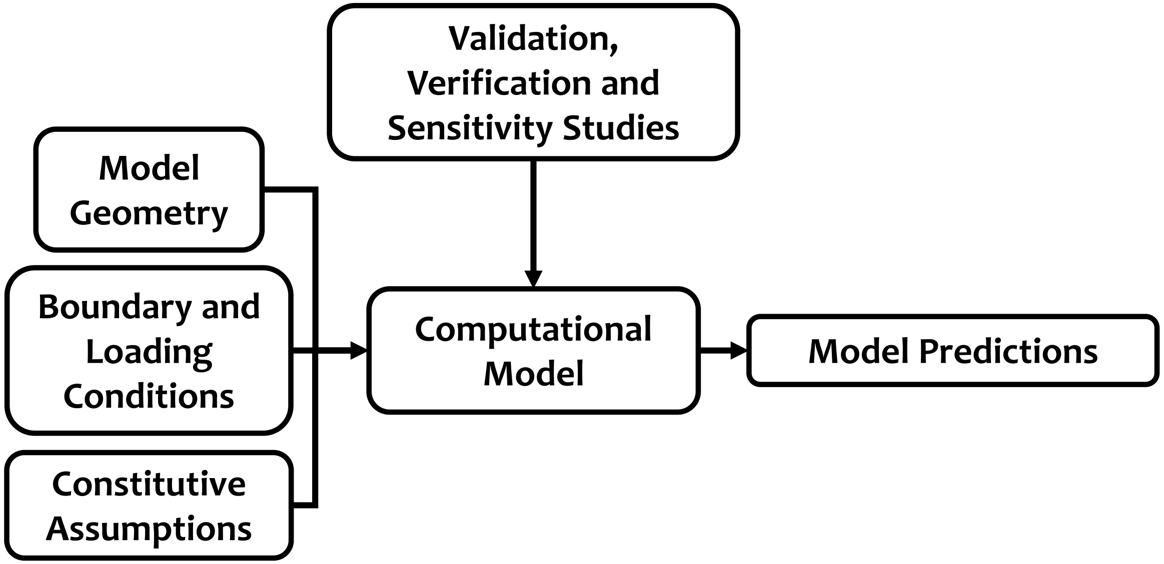
- Computational models can be used to:
  - Predict outputs that cannot be directly measured
  - Predict mechanics in living people/animals
  - Assess a larger parameter space than experimentally feasible
  - Design new constructs (e.g., tissue engineering)
- Reasons for using models:[1]
  - Safety of live subjects and ethical considerations limit the extent of *in-vivo* testing
  - Cost of experiments (and availability of certain tissues)

[1]Burkhart+, *J Biomech*, 2013.

Model Workflow

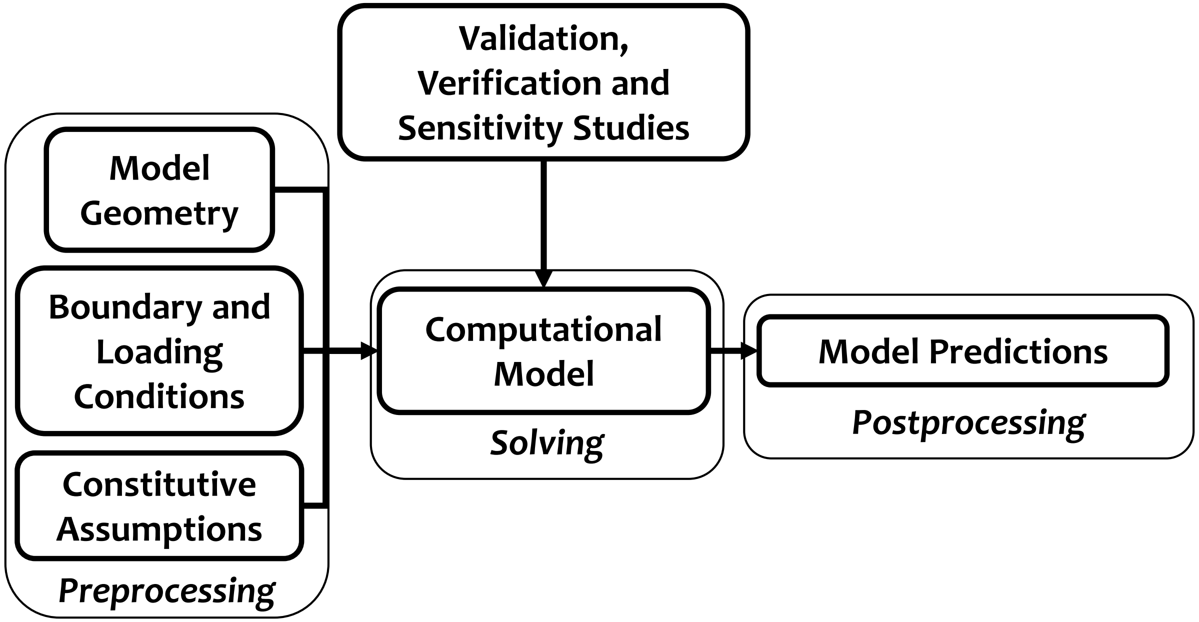
- Experimental design
  - What do you want out of the model?
  - What experimental inputs do you require?
  - What are the V&V and sensitivity studies plans?
- Preprocess
- Solve
- Postprocess
- (somewhat iterative)

Modeling Pipeline



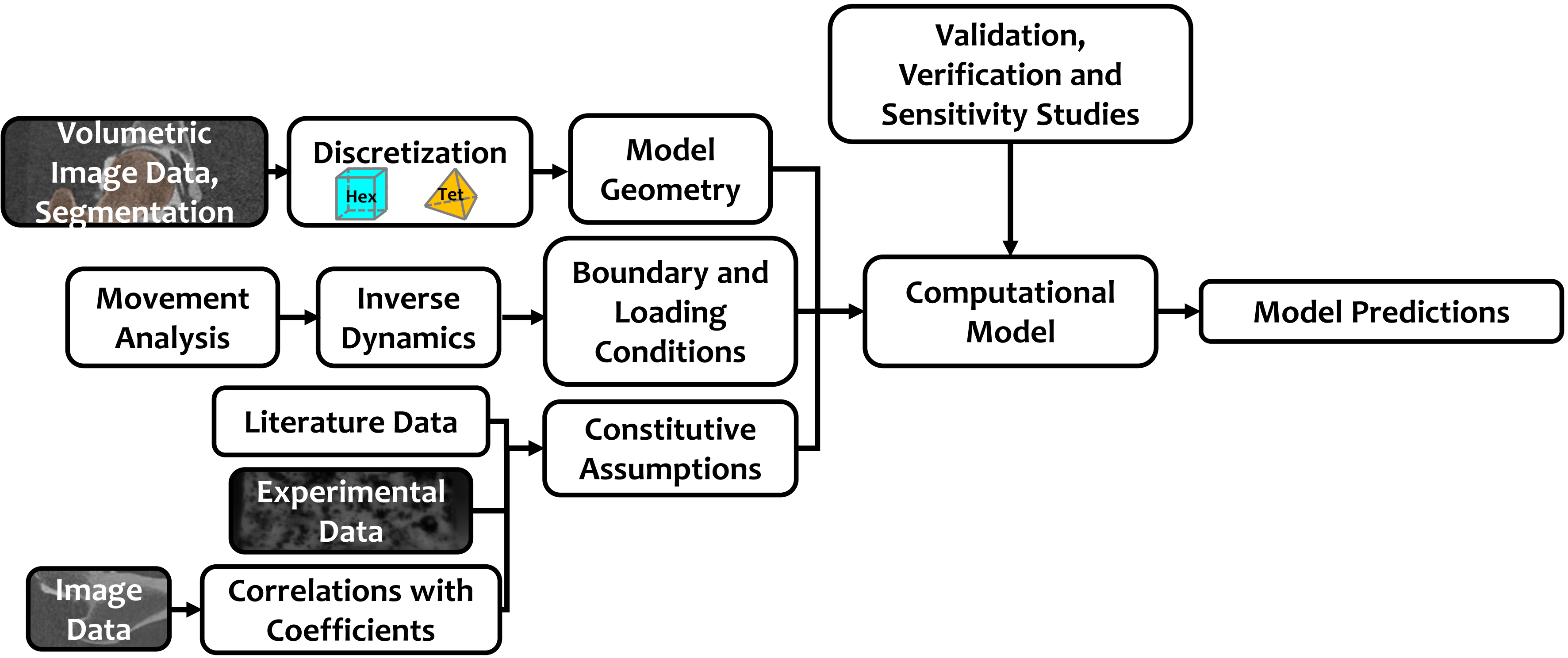
Adapted from Henak+, *J Biomech*, 2013.

Modeling Pipeline



Adapted from Henak+, *J Biomech*, 2013.

Modeling Pipeline



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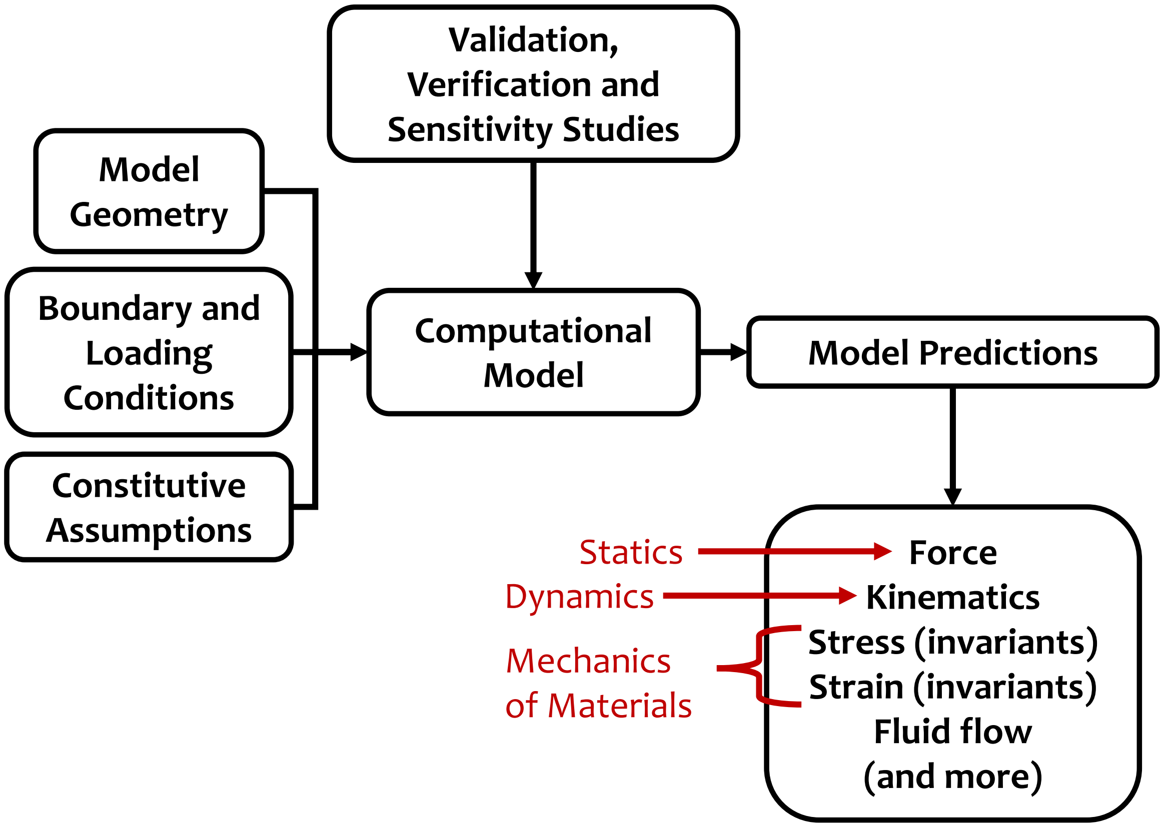
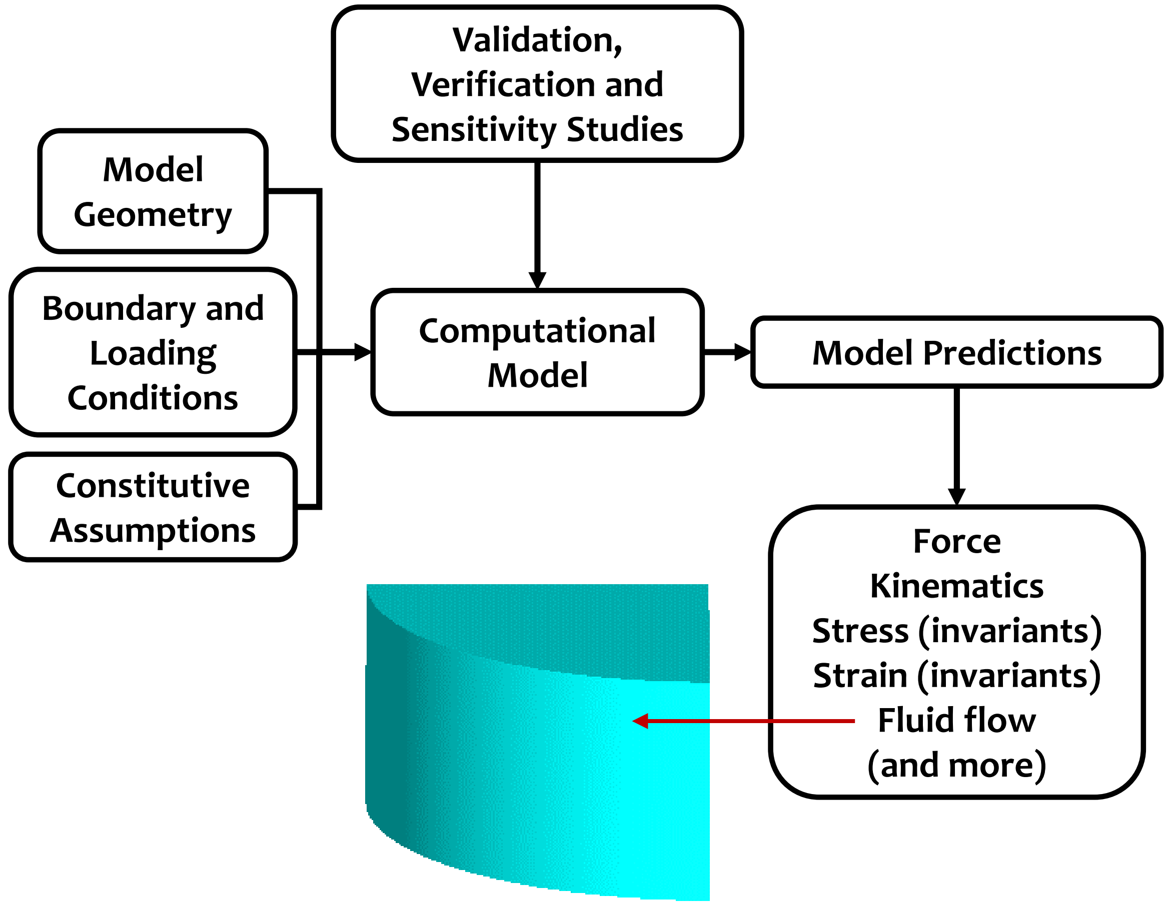
Modeling Pipeline



Adapted from Henak+, *J Biomech*, 2013.

Modeling Pipeline



Adapted from Henak+, *J Biomech*, 2013.

Modeling Platforms

- FEBio
- Abaqus
- ANSYS
- NIKE3D
- LS-DYNA
- ADINA
- COMSOL (Multiphysics)
- CAD/CAE built-ins
- Custom codes (should always document code verification)

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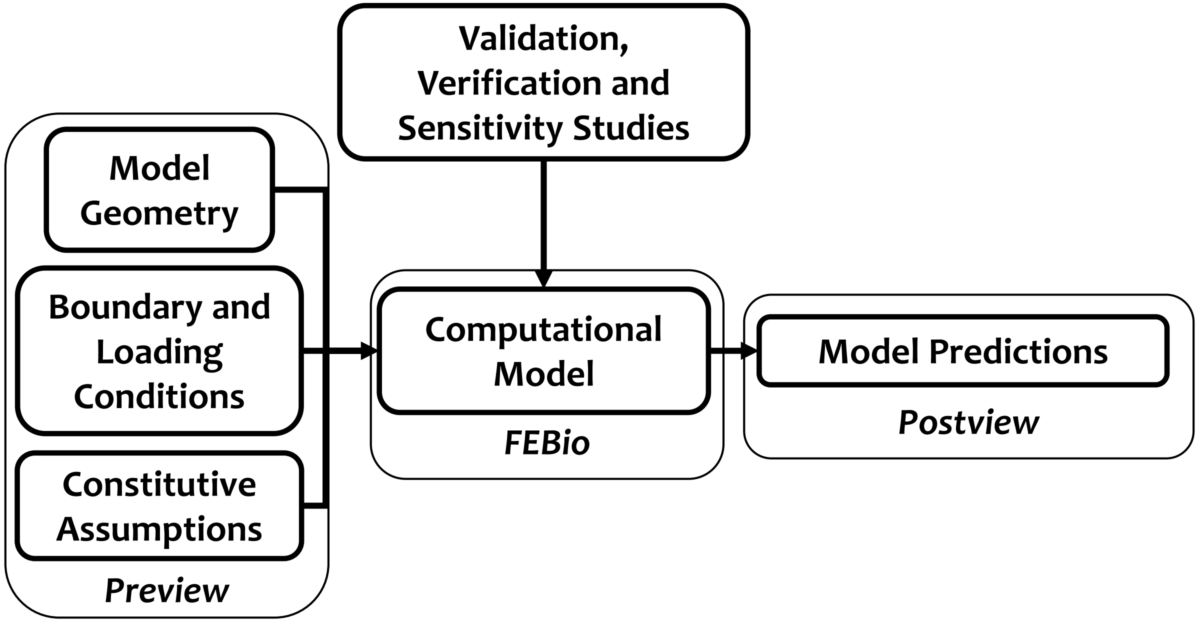
FEBio

- FEBio is an open-source FE suite (funded by NIH, free for research/teaching purposes)
- Download FEBio onto your computer from febio.org (you will also want PreView and PostView)
- If you use another FE solver for your research and want to use it in this class, discuss this with me this today

Modeling Pipeline – Example in FEBio



Adapted from Henak+, *J Biomech*, 2013.

Designing studies with FE

- General study design aims to:
  - Answer hypotheses
  - Develop new technology
  - Answer fundamental questions
- When choosing the tools (e.g., if selecting FE), answer:
  - Will the results be valid?
  - Will the costs be acceptable?
  - Is there an alternative, preferred method?

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Designing studies with FE (2)

- Design
  - What do you want out of the model?
  - What experimental inputs do you require?
  - What are the V&V and sensitivity studies plans?
- Computational models can be used to:
  - Predict outputs that cannot be directly measured
  - Predict mechanics in living people/animals
  - Assess a larger parameter space than experimentally feasible
  - Design new constructs (e.g., tissue engineering)

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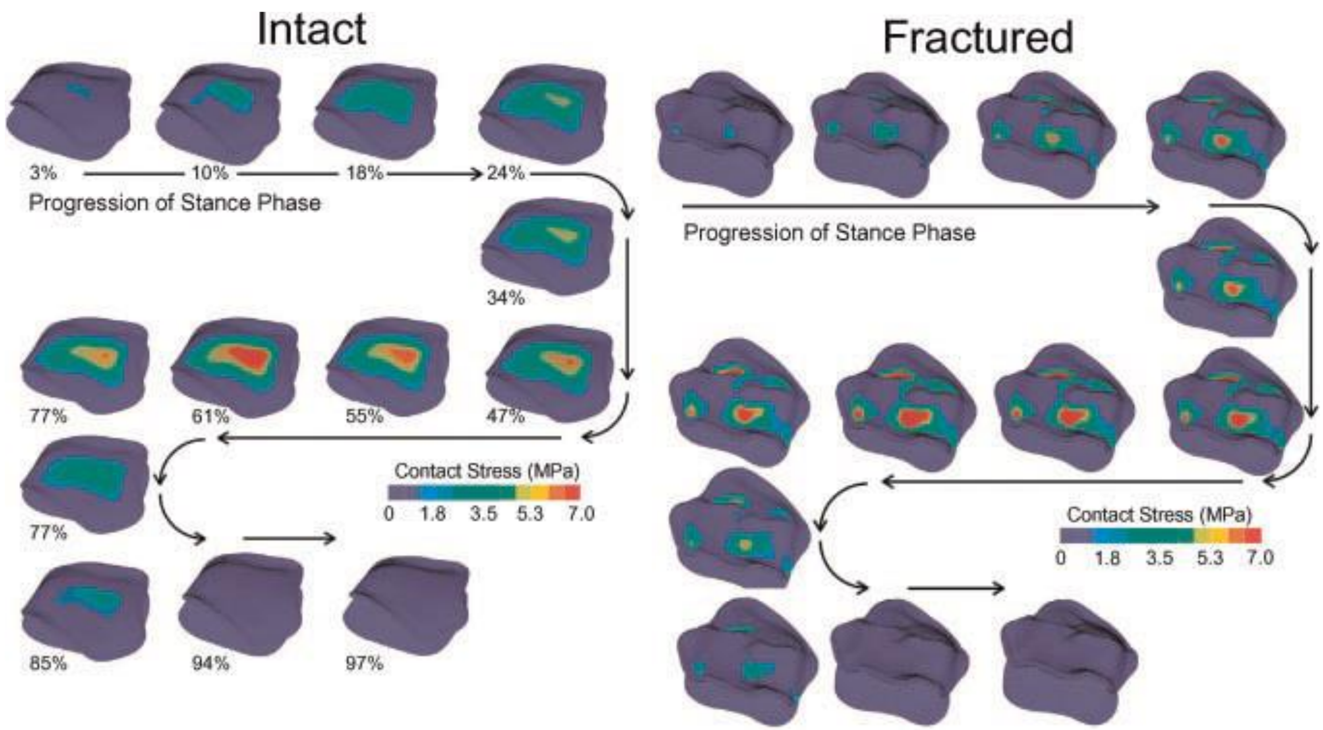
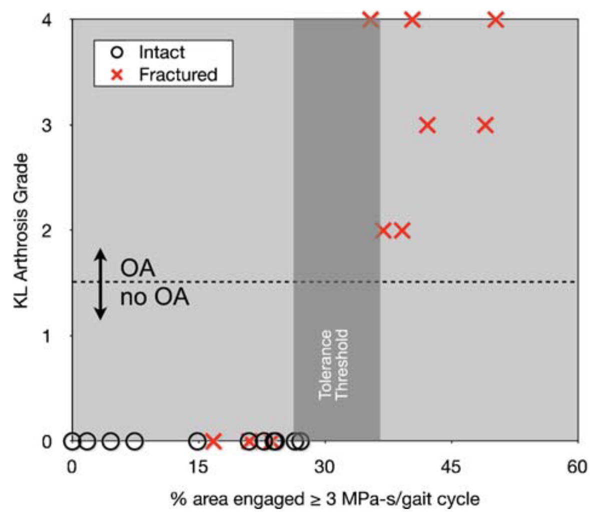
Example FE Study: Ankle Contact Pressure



Patient-specific analysis after intra-articular fracture[1]



Elevated cartilage contact stress as the link between intra-articular fracture and post-traumatic OA[2]

[1]Li+, *J Orthop Res*, 2008.
[2]Anderson+, *J Orthop Res*, 2011.

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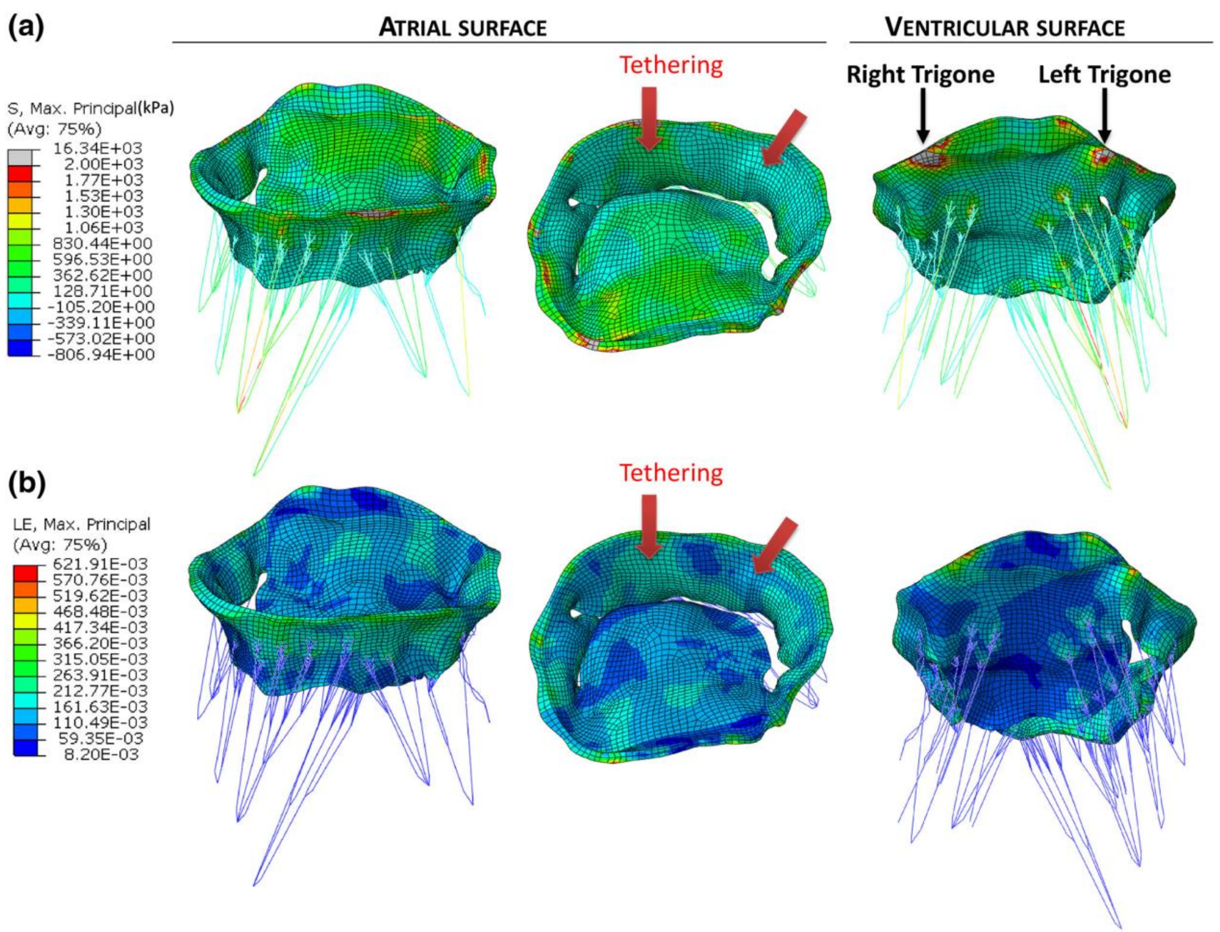
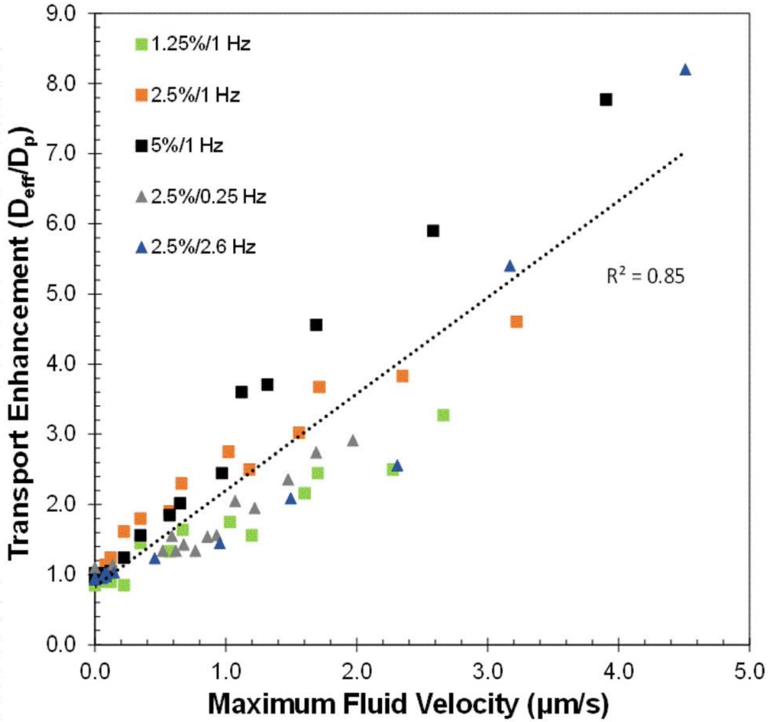
Example FE Study: Mitral Valve Regurgitation

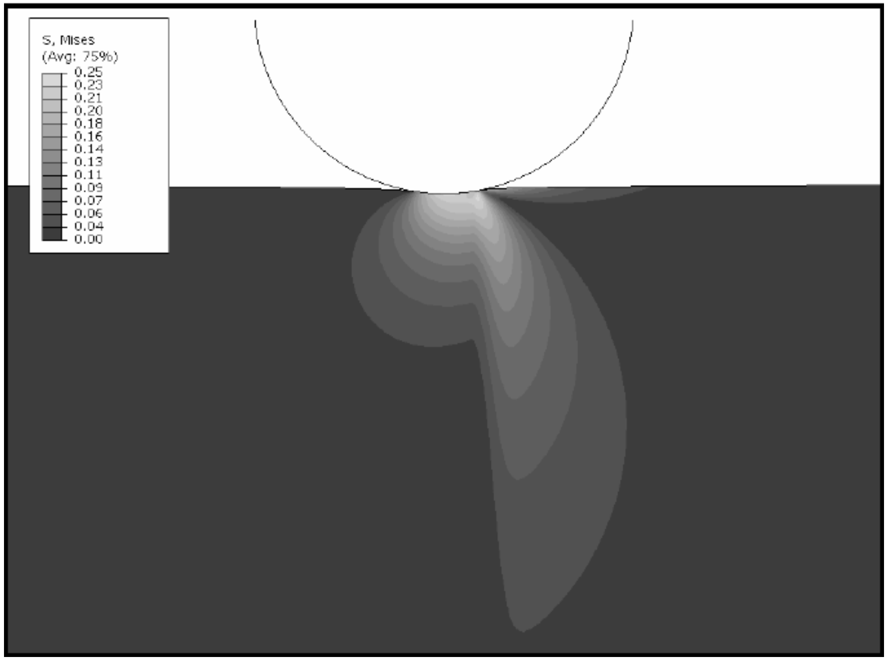


Pham+, *CV Engineering and Technology*, 2017.

Example FE Studies Using Primitive Geometry



Transport of large solutes in cartilage (experimental) versus fluid velocity (FE)[1]



Accuracy of experimental indentation for assessing spatial heterogeneity in material properties[2]

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[1]DiDomenico+, *J Biomech Engg*, 2017.
[2]Armitage and Oyen, *Acta Biomat*, 2016.

Verification, Validation and Sensitivity Studies

- Methods to establish confidence in modeling results
  - Within statistical bounds
  - More complicated with more complex models
- Level of confidence depends on what will be done with model outcomes
  - Do the results directly impact patients?

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Model Verification[1]

- *Verification* = ensuring that the equations are being solved correctly
  - *Code verification* = ensuring that mathematical models and solution algorithms are working correctly.
    - Comparisons with analytical solutions.
    - Comparisons with benchmark problems from other codes.
    - Single element tests.
  - *Calculation verification* = ensuring that the solution is free from discretization artifact.
    - Mesh convergence.

[1]ASME V&V Guide Overview.

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Model Validation[1-3]

- *Validation* = ensuring that the correct equations are being solved.
  - *Direct validation* = one-to-one comparison against a matched experimental set-up.
  - *Indirect validation* = comparison to existing or averaged data set.
- To the extent possible, model validation should be done for the outputs that the model is intended to predict.

[1]ASME V&V Guide Overview.
[2]Viceconti, *Clin Biomech*, 2005.
[3]Henninger+, *Proc I Mech H*, 2010.

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Sensitivity Studies[1]

- Sensitivity studies assess the effects of error in model inputs on model outputs.
  - Material constants
  - Geometry
  - Boundary conditions, loading conditions
- Sensitivity studies can also provide fundamental insight into the behavior of the modeled system.
- Procedure:
  - Perturb one variable at a time, evaluate the change in the output
  - Use Monte Carlo analysis for large-scale parametric analyses
- Mitigate sensitivity by improving model inputs (e.g., collecting more experimental data)

[1]Henninger+, *Proc I Mech H*, 2010.

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Overview of User Responsibilities

- User is ultimately responsible for the outcomes/decisions made as a result of her conclusions
- User has ethical obligation to ensure (to the best of her abilities) that model results are accurate, and to state any known or potential limitations
- User has responsibility to effectively communicate the necessary parts of model development, analysis, limitations, etc., to others who will make decisions based on model outcomes

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Challenges and Background

- Computational models have become more prevalent with advances in software and modeling platforms
  - This has brought less transparency in model process (e.g., analyst's decisions and solution methods)[1]
- "Model definitions and development procedures are tightly coupled to the simulation method and solver capabilities"[1]
- Details are sometimes omitted in publication due to space constraints[1]
- There is currently no widely adopted guideline for FE reporting in biomechanics

[1] Erdemir+, *J Biomech*, 2012.

Proposed Reporting Guidelines[1]

- Intent: user reporting guidelines to demonstrate that analyst has met her responsibilities
- Divided into six main sections, with suggested minimum and additional outputs to report (notes to follow are highlights relevant to this course, with bolded items expected in project documentation)

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[1]Erdemir+, *J Biomech*, 2012.

Proposed Reporting Guidelines: Model Identification[1]

- Physiological domain
  - Motion
  - Deformation/loading
- Mechanical domain (basic mathematic description)
- **Structure(s)**
- State of organism: *in vivo, ex vivo, in vitro*
- Population demographics
- Disease state
- **Spatial scale (with units)**
- **Time scale (with units)**
- **Primary utility**
- Primary highlight (most innovative feature of model)
- **Limitation(s)**
- **References to prior publication**

[1]Erdemir+, *J Biomech*, 2012.

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Proposed Reporting Guidelines: Model Structure[1]

- Provide information for reproducing the model
- **Loading and boundary conditions**
  - Type (displacement or load)
  - Location
  - Magnitude (with units), direction
  - Time history
- **Output variable(s)**
- **Source of model geometry**
  - Include imaging modality and resolution if applicable
- Reference (undeformed) configuration
- **Mesh**
  - Element type
  - Mesh density
- **Constitutive model(s)**
- **Interactions (e.g., contact)**
  - Components
  - Type
  - Formulation
  - Properties

[1]Erdemir+, *J Biomech*, 2012.

Proposed Reporting Guidelines: Simulation Structure[1]

- **Software**
  - Name
  - Version
  - Solution strategy (FEBio is an implicit, nonlinear finite element solver[2])
- **Numerical algorithms**
- **Convergence criteria**
- Post-processing approach (especially if secondary outcomes are calculated)

[1]Erdemir+, *J Biomech*, 2012. [2]FEBio Theory Manual.

Proposed Reporting Guidelines: Verification[1]

- **Verification methods**
- Correctness of verification (code verification for anything that is user-implemented)
- Sensitivity to simulation settings (e.g., convergence criteria, numerical algorithm)
- **Mesh convergence**
- Assessment of repeatability (e.g., simulation on different platforms)

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[1]Erdemir+, *J Biomech*, 2012.

Proposed Reporting Guidelines: Validation[1]

- **Validation procedure** (or lack thereof)
- **Validated output(s)**
- **Overall modeling assumptions**
- Relevance of boundary and loading conditions
- **Justification of model parameters**
- **Data used for model development** (can be references to the literature)
- **Data use for model comparison** (can be references to the literature)
- **Sensitivity analysis**
- Predictive capability and limitations

[1]Erdemir+, *J Biomech*, 2012.

Proposed Reporting Guidelines: Availability[1]

- Contact info for responsible investigator(s)
- Licensing info
- Website(s) for:
  - Download
  - Development
  - Public commentary, responses and rating

Example file in Appendix[1]

[1]Erdemir+, *J Biomech*, 2012.

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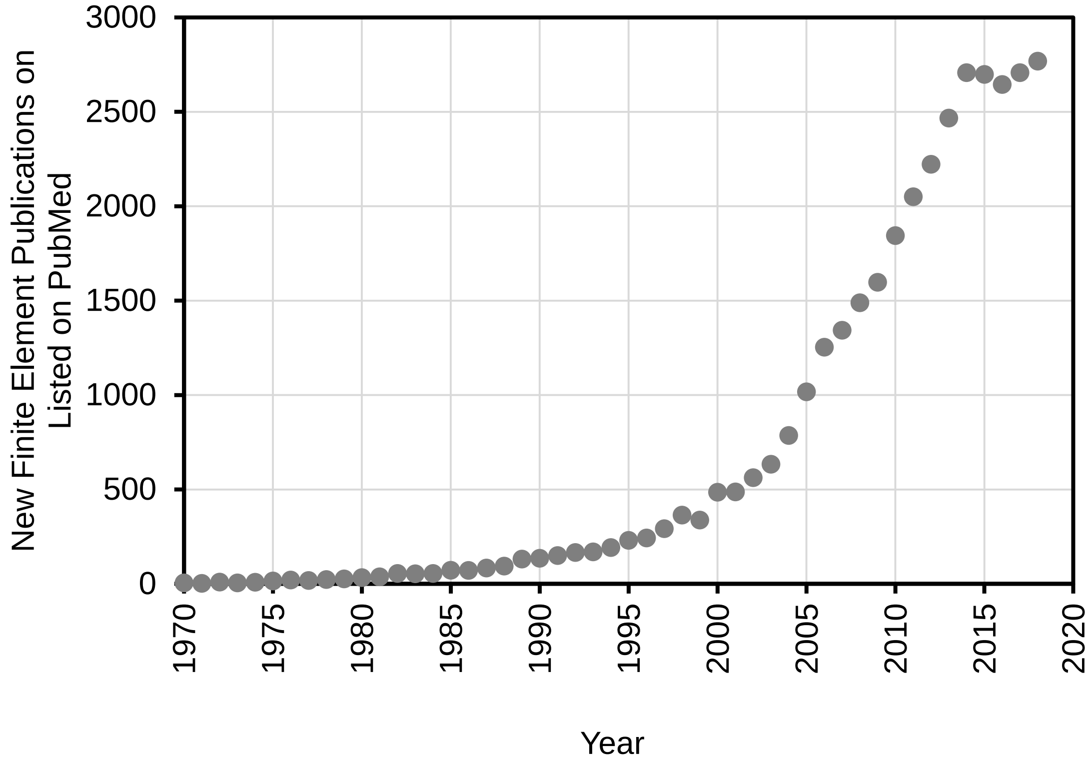
Reporting Locations

- Publications and technical communications
  - Some journals allow supplemental files or appendices
- Data/file sharing
  - SimTK
  - Lab websites or other data sharing sites (note that there are certain rules that must be followed depending on where funding comes from, where results are published, and who owns the data)

Other Reporting Guidelines

- Journal specific: Annals of Biomedical Engineering
  - "Modeling developments should conform to standard modeling practice"
  - "…the sensitivity of such solutions/results to these parameters for the numerical values used in simulations should be evaluated."
- Journal specific: Clinical Biomechanics
  - "The tools themselves, such as finite element analysis, are valid when used correctly."
  - "Every effort should be expended to ensure that the finite element model is verified and validated and that its output is correctly interpreted before its predictions can be considered to have any clinical value."
  - Specifically suggest reporting (specifics depend on use of model): model selection, verification, proper parameter identification, sensitivity analysis, inter-subject variability, validation against controlled in-vitro experiments, risk-benefit analysis, retrospective studies, prospective studies

The Reader's Responsibilities



- Are all of these publications reliable?
- You (as the reader) are responsible for deciding

The Reader's Responsibilities

- Review to evaluate the authors':
  - Verification
  - Validation
  - Sensitivity Studies
  - (this may require digging through their references)
- Decide whether the authors appropriately stated outcomes and whether limitations are given sufficient weight

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Finding relevant, high-quality publications (for course project)

- Publications can be found through Pubmed or Google Scholar, or through journals
- Some good journals for biomechanics modeling literature (not exhaustive, just a place to start):
  - *Journal of Biomechanical Engineering*
  - *Biomechanics and Modeling in Mechanobiology*
  - *Journal of Biomechanics*
- If you are uncertain about the journal/publication quality, you can run it by me.

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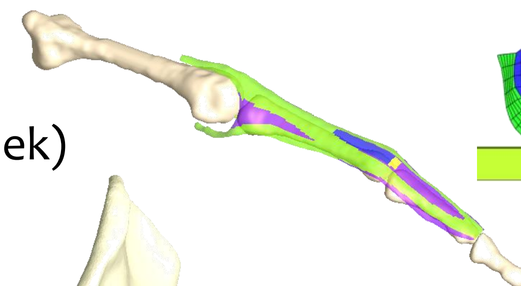
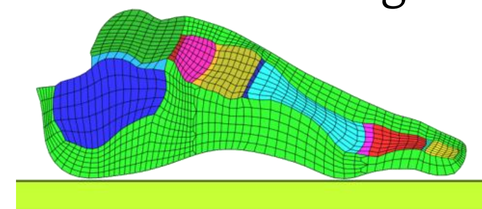
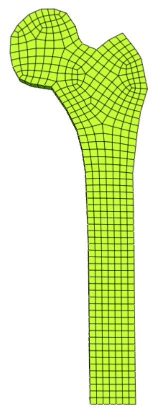
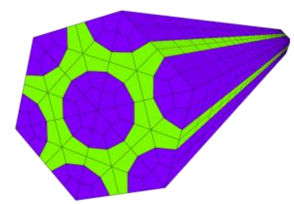
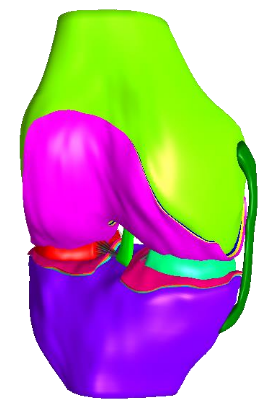
Course Project

- Purpose: provide an opportunity to actually do most steps in the FE modeling pipeline that we discuss in class
- Deliverables
  - Project proposal (due next week)
  - Project literature review
  - Midterm report
  - Project presentation
  - Final report

- Model choices
  - Primitive meshes
  - Existing meshes
  - If you have a model from your research or lab that you would like to use, talk to me
- Start to consider your group and project (10-15 minute introductions/discussion)
  - 2-3 people per group for undergraduates
  - Individual for graduates

Project proposal is due on 1/31/19, so find your group soon!